

A Method of Calculating the Characteristic Parameters of Lightning Overvoltage

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Abstract

In order to protect the equipments and make rules for lightning protections, it's essential to record accurate lightning overvoltage waves. The use of serial reactors which are intended to limit large current brings new problems for measuring the lightning overvoltage. This paper analyzes the change of the lightning overvoltage through the serial reactor and the bus, and concludes that the overvoltage at the entrance of the transformer can't reflect the invasion voltage of the substation well. In review of the position of the arrester in the substation, a method for calculating the lightning overvoltage is presented by using the leakage current of the arrester, and reverse iterative method is put forward in the calculation of the PINCETI model. The leakage current of 110kV arrester is simulated with ATP-EMTP and the amplitude and steepness of the lightning overvoltage are calculated, which verified the effectiveness of the proposed method.

Keywords

MOA; Lightning Overvoltage; Leakage Current; Nonlinear Resistance; Reverse Iterative Method

Introduction

With the development of power system, the height of the overhead transmission lines continues to increase and the possibility that power outages are caused by lightning is also increasing. Accurate lightning overvoltage waveforms can help us to analyze the reason of accidents, and improve insulation coordination [1-2].

There are a few ways to get invaded overvoltage waveforms, but they have some defects. PTs and CVTs don't have excellent transient characteristics [3], capacitance dividers may bring potential dangers [4-5], extra voltage sensors may cause the ground line break [6], and the method that the voltage is calculated according to leakage current doesn't reflect the invaded voltage [7].

The use of serial reactors can limit short circuit currents, while they change the propagation

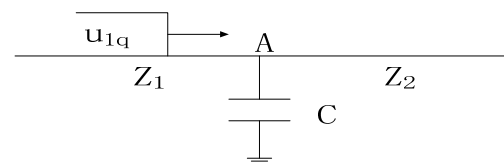
characteristics. This paper analyzes the influence of bus and serial reactors and simulates it using ATP-EMTP.

MOA (Metal Oxide Arrester) are widely used in power system to limit overvoltage and protect electrical equipments for its excellent performance. Because the arrester is the first equipment that the overvoltage goes through, a method to calculate lightning overvoltage using the leakage current is presented and is verified by ATP-EMTP simulation results.

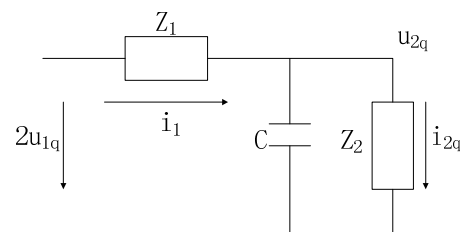
The Propagation of Overvoltage In Station

The capacitive and inductive equipments, the distributed capacitance of equipments and the mutual capacitance between equipments can impact on the spread of the lightning overvoltage [8-9].

1) The Effect of Capacitance



(A) THE SCHEMATIC DIAGRAM OF LIGHTNING OVERVOLTAGE THROUGH CAPACITANCE



(b) The equivalent circuit

FIG.1 PROMULGATION CHARACTERISTICS OF LIGHTNING OVERVOLTAGE WAVE AT THE SHUNT CAPACITOR

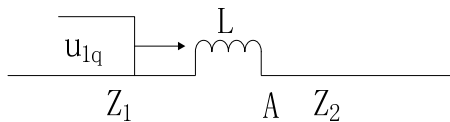
As shown in Fig.1, when the lightning overvoltage passes the capacitor C , according to Peterson Law, the refracted voltage can be calculated from

formula (1):

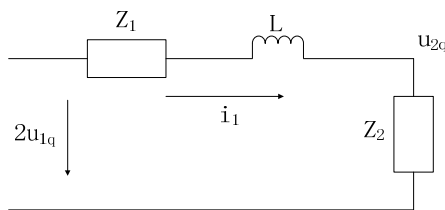
$$u_{2q} = i_{2q} Z_2 = \frac{2Z_2}{Z_1 + Z_2} u_{1q} (1 - e^{-t/T}) \quad (1)$$

Where: $T = Z_1 Z_2 C / (Z_1 + Z_2)$.

2) The Effect of Inductance



(A) THE SCHEMATIC DIAGRAM OF LIGHTNING OVERVOLTAGE THROUGH INDUCTANCE



(B) THE EQUIVALENT CIRCUIT

FIG.2 PROMULGATION CHARACTERISTICS OF LIGHTNING OVERVOLTAGE WAVE THROUGH SERIAL INDUCTOR

When the lightning overvoltage passes the serial inductor L , the refracted voltage can be calculated according to formula (2)

$$u_{2q} = i_{2q} Z_2 = \frac{2Z_2}{Z_1 + Z_2} u_{1q} (1 - e^{-t/T}) \quad (2)$$

Where: $T = L / (Z_1 + Z_2)$.

3) ATP-EMTP Simulation

A model of 110kV substation is built as Fig.3 [10]. It has three lines and Line3 has serial reactor L . Where: the reactor $L=3H$ and the distributed capacitance of the bus $C=0.006 \mu F$. Line 3 is struck at 0.001s and the voltage waveforms monitored are presented in Fig.4. (u_a is the voltage at arrester and u_t is at the bolster of the transformer).

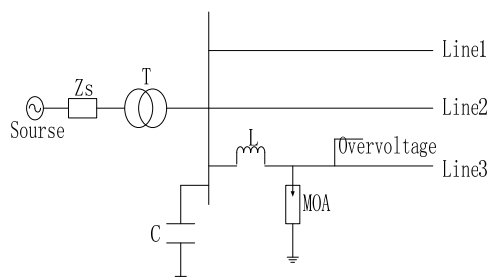


FIG.3 THE SCHEME OF A 500KV SUBSTATION

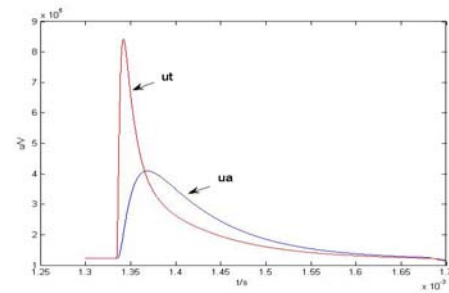


FIG.4 THE LIGHTNING OVERVOLTAGE WAVE AT THE POSITION OF THE ARRESTER AND THE TRANSFORMER

In Fig.4, the voltage waveforms are very different in amplitude and steepness monitored at the two places and the voltage at the bolster can't reflect the invaded voltage of the substation. So, a method to calculate the characteristic parameters using leakage current of MOA is posted.

Calculation of the Characteristic Parameters of Lightning Overvoltage

The amplitude and steepness are the most important parameters of lightning overvoltage, which can direct to analyze the cause of malfunction and make protection rules. The leakage current can be measured by current sensors and a method named reverse iterative method is posted to calculate overvoltage.

1) The Measurement of Leakage Current

As shown in Fig.5, the system includes three parts [11-15]: current sensor, data acquisition and transmission module and data analysis module. When the voltage across arrester is too high, the leakage current gets high and the relationship between voltage e measured by secondary coil induced in coil and the leakage current can be calculated as formula (3)-(4)

$$e = \frac{d\psi}{dt} = NS \frac{dB}{dt} = \frac{NS\mu_0}{2\pi r} \cdot \frac{di}{dt} \quad (3)$$

$$i = \frac{2\pi r}{\mu_0 NS} \int e dt \quad (4)$$

Where:

e --- voltage induced in the secondary coil;

i --- leakage current;

N --- turns of secondary coil;

B --- flux density around the ground line;

S --- area of secondary coil;

r --- radius of secondary coil;

ψ --- flux in secondary coil;

μ_0 --- permeability of air.

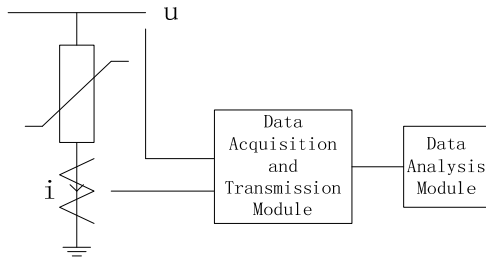
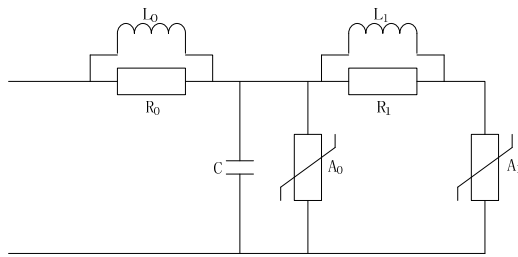


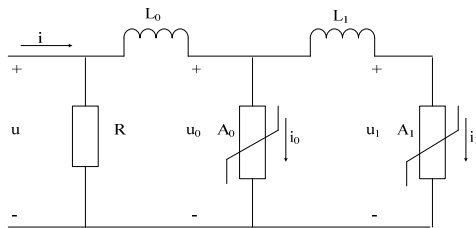
FIG.5 ON-LINE MONITORING SYSTEM OF LEAKAGE CURRENT OF ARRESTER

2) MOA Models

Two models of MOA are shown in Fig.6, IEEE model and PINCETI model. The parameters of IEEE model are more difficult to determine, and the parameters of PINCETI model only depend on test parameters [16-18]. In this paper, the overvoltage across the arrester is calculated on the base of PINCETI model.



(a) IEEE Model



(b) PINCETI Model

FIG.6 SIMPLIFIED MODEL OF ZINC OXIDE ARRESTERS

In PINCETI model, R equals $1M\Omega$; The u - i characteristics of nonlinear resistances A_0 and A_1 are shown in Fig.7; To calculate L_0 and L_1 , equations (5)-(6) can be used:

$$L_1 = \left(\frac{1}{4}\right) \left[\frac{(U_{r1/T2} - U_{r8/20})}{(U_{r8/20})} \right] U_n \quad (5)$$

$$L_0 = \left(\frac{1}{12}\right) \left[\frac{(U_{r1/T2} - U_{r8/20})}{(U_{r8/20})} \right] U_n \quad (6)$$

$U_{r1/T2}$ represents the residual voltage at 10kA fast

front current surge ($r1/T2 \mu s$); $U_{r8/20}$ represents the residual voltage at 10kA fast front current surge with a $r8/20 \mu s$ shape; U_n is the rated voltage of the arrester.

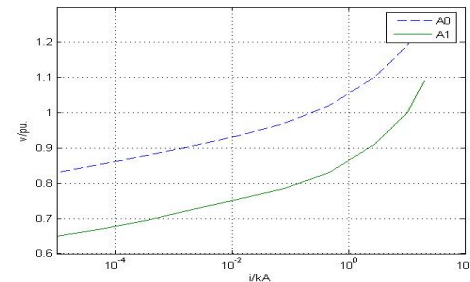


FIG.7 THE CHARACTERISTICS OF A0 AND A1 (THE VOLTAGE IS IN P.U. REFERRED TO THE $U_{r8/20}$)

3) The Mathematical Model of the Arrester

In PINCETI model, equations (7)-(11) can reflect the relationship between the voltage across the arrester and the leakage current.

$$u_0 = f_0(i_0) \quad (7)$$

$$u_1 = f_1(i_1) \quad (8)$$

$$L_1 \frac{di_1}{dt} = u_0 - u_1 \quad (9)$$

$$L_0 \frac{d(i_0 + i_1)}{dt} = u - u_0 \quad (10)$$

$$i = \frac{u}{R} + i_0 + i_1 \quad (11)$$

Where: f_0 、 f_1 represent the u - i function of nonlinear resistances A_0 and A_1 ; u is the wanted variable.

4) The Calculation of Voltage

A method named reverse iterative method is put forward in order to calculate the voltage. The basic idea of reverse iteration method is: in Fig.8, if x and y has the same variation, y has only one value in correspond with x . According to the errors between calculated and measured data, a penalty factor is introduced and y can be recalculated until the error is within the allowable range.

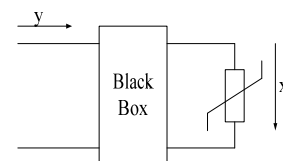


FIG.8 THE CIRCUIT CONTAINING NONLINEAR RESISTANCE

In Fig.9, f represents the function between the input and output data. If f is monotonous, x has one value to satisfy that y equals y_{ref} [19].

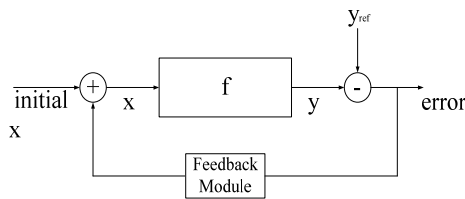


FIG.9 ANALYSIS OF BACKWARDS ITERATIVE METHOD

In Fig.6 (b), if i_1 increases, i also increases. The parameters in PINCETI model can be calculated using reverse iterative method.

At any time k , the specific solution steps are as follows.

① Divide $u-i$ curves of A0 and A1 into n segments, discrete formulas (9)~(11) and assume that each segment is linear.

② Assign i_1 an initial value $i_1(k)$ and determine which segment $i_1(k)$ belongs to. If $i_1(k)$ belongs to m_1 , then the voltage across the resistance A1 is

$$u_1(k) = f_1(i_1(k)) = u_{1m10} + (i_1(k) - i_{1m10}) \cdot (u_{1m11} - u_{1m10}) / (i_{1m11} - i_{1m10}) \quad (12)$$

Where: (i_{1m10}, u_{1m10}) 、 (i_{1m11}, u_{1m11}) represent the start and the end of segment m_1 .

③ Calculate voltages across the nonlinear resistor A0 and the inductor L1 :

$$u_{L1}(k) = L_1 \frac{i_1(k) - i_1(k-1)}{\Delta t} \quad (13)$$

$$u_0(k) = u_1(k) + u_{L1}(k) \quad (14)$$

④ If $u_0(k)$ belongs to m_0 , the current through A0 is

$$i_0(k) = i_{0m00} + (u_0(k) - u_{0m00}) \cdot (i_{0m01} - i_{0m00}) / (u_{0m01} - u_{0m00}) \quad (15)$$

Where: (i_{0m00}, u_{0m00}) 、 (i_{0m01}, u_{0m01}) represent the start and the end of segment m_0 .

⑤ Calculate the current through L0 and the voltage across L0 :

$$i_{L0}(k) = i_0(k) + i_1(k) \quad (16)$$

$$u_{L0}(k) = L_0 \frac{i_{L0}(k) - i_{L0}(k-1)}{\Delta t} \quad (17)$$

⑥ Calculate lightning voltage u

$$u(k) = u_{L0}(k) + u_0(k) \quad (18)$$

⑦ Calculate leakage current

$$i(k) = i_0(k) + u(k) / R \quad (19)$$

⑧ If the error between $i(k)$ and $i_{ref}(k)$ is not within the allowable range, according to equation (20), correct $i_1(k)$, and repeat the above calculation processes until the error is small. Where α is the penalty factor.

$$i_1(k) = i_1(k) + \alpha \cdot (i(k) - i_{ref}(k)) \quad (20)$$

The value u in process ⑥ is what we want.

EMTP Simulation

1) Parameters of Arrester

A 110kV transmission system is simulated using ATP-EMTP. The type of MOA is Y10W5-100/248, and its electrical characteristics are shown in Tab.1 [20]. (voltages are in kV)

TAB.1 MEASURED ELECTRICAL PARAMETERS OF MOA: Y10W5-100/248

U_n	U_r	U_c	$U_{30/60,0.5k}$	$U_{45/90,0.5k}$	$U_{45/90,1k}$	$U_{45/90,2k}$
11	10	7	211	203	213	217
0	0	3				

$U_{8/20,5k}$	$U_{8/20,10k}$	$U_{8/20,20k}$	$U_{4/10,40k}$	$U_{4/10,65k}$	$U_{1/5,10k}$
231	248	272	316	365	273

In Tab.1, U_n is the rated voltage of the system; U_r is the rated voltage of MOA; U_c is the continuous operating voltage of MOA; $U_{r1/T2, Iamp}$ represents the residual voltage for surge current impulse with Iamp amplitude and $r1/T2 \mu s$ shape.

The characteristics of A0 and A1 in PINCETI model are in Tab.2.

TAB.2 V-A CHARACTERISTICS OF A0,A1

I/kA	0.01	0.1	1	2	4
U/kV	217.0	238.0	260.4	269.7	279.0
	190.5	199.0	210.8	221.6	229.4
6	8	10	12	14	16
282.1	289.9	294.5	299.1	305.3	310.0
232.5	237.2	240.3	241.9	245.0	246.5

2) Results

After the line was struck by lightning, the arrester discharged to release lightning energy. And the leakage current measured is shown in Fig.10.

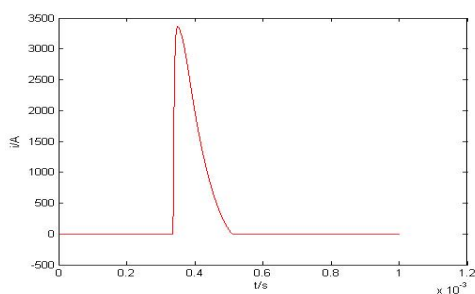


FIG.10 THE LEAKAGE CURRENT OF THE ARRESTER

In Fig.11, the voltages calculated and measured across the arrester are shown (blue dotted line represents the calculated data and the red line represents the measured data).

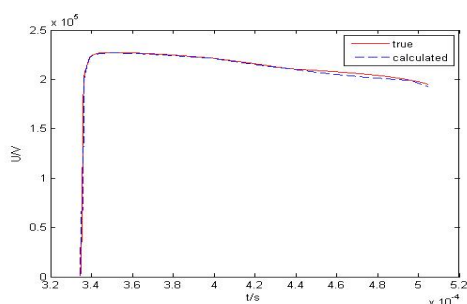


FIG.11 THE COMPARISON BETWEEN THE CALCULATED DATA AND THE TRUE DATA

The two parameters amplitude and steepness of the lightning overvoltage are in Tab.3. The steepness is represented by the time of rise.

TAB.3 THE COMPARISON OF THE CHARACTERISTICS BETWEEN THE CALCULATED DATA AND THE TRUE

	Calculated data	Measured data	Error
Amplitude	$2.2676 \times 10^6 \text{ V}$	$2.2733 \times 10^6 \text{ V}$	0.25%
Time of rise	$3.505 \times 10^{-4} \text{ s}$	$3.503 \times 10^{-4} \text{ s}$	0.057%

In Tab.3, the parameters of the lightning overvoltage can be calculated correctly with the method presented in this paper.

Conclusion

This paper simulates and analyzes the impact of serial reactor and bus, and concludes that the voltage at bolter of transformers can't reflect the lightning overvoltage invaded; In order to calculate the lightning overvoltage, a method named reverse iteration method is posted; The voltage calculated with this method is very similar to the real voltage, and this method is verified effective.

The method presented in this paper can calculate the

amplitude and steepness of the lightning overvoltage correctly, which is helpful to analyze malfunction reason and make protection measures.

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